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THE LEGACY OF WETLAND DRAINAGE ON THE REMAINING PEAT IN THE SACRAMENTO – SAN JOAQUIN DELTA, CALIFORNIA, USA

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Abstract: Throughout the world, many extensive wetlands, such as the Sacramento-San Joaquin Delta of California (hereafter, the Delta), have been drained for agriculture, resulting in land-surface subsidence of peat soils. The purpose of this project was to study the *in situ* effects of wetland drainage on the remaining peat in the Delta. Peat cores were retrieved from four drained, farmed islands and four relatively undisturbed, marsh islands. Core samples were analyzed for bulk density and percent organic carbon. Macrofossils in the peat were dated using radiocarbon age determination. The peat from the farmed islands is highly distinct from marsh island peat. Bulk density of peat from the farmed islands is generally greater than that of the marsh islands at a given organic carbon content. On the farmed islands, increased bulk density, which is an indication of compaction, decreases with depth within the unoxidized peat zone, whereas, on the marsh islands, bulk density is generally constant with depth except near the surface. Approximately 55–80% of the original peat layer on the farmed islands has been lost due to land-surface subsidence. For the center regions of the farmed islands, this translates into an estimated loss of between 2900–5700 metric tons of organic carbon/hectare. Most of the intact peat just below the currently farmed soil layer is over 4000 years old. Peat loss will continue as long as the artificial water table on the farmed islands is held below the land surface.

Key Words: bulk density, compaction, marsh, microbial oxidation, organic carbon, radiocarbon age determination, subsidence

INTRODUCTION

Extensive tracts of wetlands have been drained for agriculture, creating major agricultural regions in the United States and many other places around the world (Schothorst 1977, Penland and Ramsey 1990, Ibanez et al. 1997, Nieuwenhuis and Schokking 1997, Hambright and Zohary 1999). In these regions, the former wetland soils are often subject to major changes in structure and function, which ultimately result in land-surface subsidence. The consequences of land-surface subsidence are numerous including mass loss of soil, reduction in soil fertility, lowering of land-surface elevation relative to sea level, reduction in ecosystem services such as flood control and sediment trapping, and property damage due to settling of structures (Stephens et al. 1984, Prokopovich 1985, Penland and Ramsey 1990, Conner and Day 1991). In addition, land-surface subsidence in farmed areas adjacent to waterways necessitates continuous maintenance of levees because of the increased elevation differentials between waterways and adjacent farmlands (Ingebritsen and Ikehara 1999). Finally, land-surface subsidence also contributes to global warming because oxidation of peat soils can liberate vast quantities of CO_2 (Armentano 1980, Stephens et al. 1984).

The Sacramento-San Joaquin Delta (hereafter, the Delta) of California is a prime example of a huge wetland area that was drained for agriculture and has subsequently experienced land-surface subsidence. The Delta, situated at the confluence of the Sacramento and San Joaquin rivers, was once a 1400 km^2 tidal marsh with land-surface elevation near local mean sea level (Gilbert 1917). In the central and western Delta, accretion of inorganic sediment and organic matter for a period of approximately 7000 years resulted in a peat layer of between 2–15 m thick (Dachnowski-Stokes 1936, Weir 1950, Atwater and Belknap 1980, Drexler et al. 2007). Beginning in the mid-1800s, the Delta was drained for agriculture. By the 1930s, the entire area was transformed by extensive levee-building into an agricultural landscape with about 57 farmed islands and tracts (Thompson 1957, Ingebritsen et al. 2000). Such alteration of the landscape initially resulted in primary land-surface subsidence through mechanical settling of the peat surface due to loss of buoyant force (Everett 1983, Ewing and Vepraskas 2006). Subsequently, secondary subsidence occurred due to shrinkage upon drying, burning of peat (a discontinued agricultural practice), wind erosion, anaerobic decomposition, dissolution of soil organic matter, ongoing consolidation due to increased drainage ditch depth, and oxidation of organic carbon in the peat (Weir 1950, Prokopovich 1985, Deverel and Rojstaczer 1996, Deverel and Leighton, 2008). Of these factors, the chief cause of secondary subsidence in the Delta has been microbial oxidation of organic carbon, whereby organic carbon in the peat is converted by microorganisms into carbon dioxide (Deverel and Rojstaczer 1996, Deverel and Leighton, 2008). Land-surface subsidence continues to this day and has resulted in over 20 farmed Delta ''islands'' with land-surface elevations between 3–8 m below sea level (California Department of Water Resources 1980, Ingebritsen et al. 2000).

The pace of land-surface subsidence in the Delta has decreased substantially over time. Maximum historic rates in the mid-twentieth century ranged from 2.8–11.7 cm yr^{-1} (Weir 1950, California Department of Water Resources 1980). In the late 1980s and 1990s, rates were found to be between 0.5–4 cm yr^{-1} (Rojstaczer and Deverel 1993, 1995, Deverel and Rojstaczer 1996, Deverel et al. 1998). The latest estimates show that rates of land-surface subsidence have continued to decrease, and now range between 0.5–3.0 cm yr^{-1} for selected islands (Deverel and Leighton 2008). Such slowing in the rate of subsidence in the Delta has been attributed to cessation of peat burning, changing land management practices, and reduced organic carbon content of surface soils (Deverel and Leighton 2008).

Several factors exert control over land-surface subsidence in drained wetlands such as the Delta. The height of the artificial water table on farmed islands determines the depth to which the peat is oxidized (Prokopovich 1985, Rojstaczer and Deverel 1993), and therefore, exerts strong control over the rate of secondary subsidence. Deverel et al (2007) showed that drainage ditches on farmed islands in the Delta are regularly excavated and cleaned in the late spring, summer, and fall in order to maintain necessary ground-water levels of 1 m or deeper for agriculture. During the rainy winter, however, ground-water levels are allowed to recharge, rising close to the land surface. This practice results in an oxidized layer of peat approximately 1 m thick, which remains unsaturated most of the year (Deverel et al. 2007). In the Everglades, Stephens et al. (1984) quantified the relationship between subsidence and depth of the water table. In their study, a water table of about 30 cm below land surface resulted in about 20% of the subsidence rate compared to a water table at 120 cm below land surface for soils with identical organic matter content and temperature regimes. Other key factors that influence the rate of subsidence include the percent of organic carbon in the peat and the thickness of the remaining peat layer (Prokopovich 1985, Rojstaczer and Deverel 1995, Ingebritsen and Ikehara 1999). Rojstaczer and Deverel (1995) demonstrated a significant positive correlation between soil organic matter content and historic subsidence rates on Sherman Island in the Delta. In addition, Deverel and Leighton (2008) showed a significant, positive correlation of subsidence rates and soil organic matter content from 1978 to 2006 on Bacon Island in the Delta.

Although there have been several studies on subsidence rates and related processes, there have yet to be any studies that have examined the *in situ* impacts of long-term subsidence on the remaining peat in the Delta. However, without such knowledge it is not possible to determine how agricultural practices have and will continue to affect the remaining peat resource. We present data from four drained, farmed islands and four relatively undisturbed, marsh islands (hereafter farmed and marsh islands, respectively) in order to compare the changes that have occurred in the peat since drainage for agriculture. The analysis is focused on peat thickness, bulk density, and percent organic carbon content of the remaining peat layer in the Delta.

STUDY SITES

The Delta is located at the confluence of the Sacramento and San Joaquin rivers, at the landward end of the San Francisco Bay Estuary, California (Figure 1). The climate in the Delta is characterized as Mediterranean with cool, wet winters and hot, dry summers (Atwater 1980). Mean annual precipitation is approximately 36 cm, but actual yearly precipitation varies from half to almost four times this amount. Over 80% of precipitation occurs from November through March (Thompson 1957). Beginning in the mid-1800s, the Delta was drained for agriculture (Thompson 1957, Atwater 1980), resulting in its current configuration of over 100 islands and tracts surrounded by 2250 km of man-made levees and 1130 km of waterways (Prokopovich 1985 (Figure 1).

In total, four pairs of study sites were chosen including four marsh islands (Browns Island, Franks Wetland, the Tip of Mandeville Tip, and Bacon Island Channel Island) and four farmed islands (Sherman Island, Webb Tract, Venice Island, and Bacon Island) (Figure 1). Such pairing of nearby

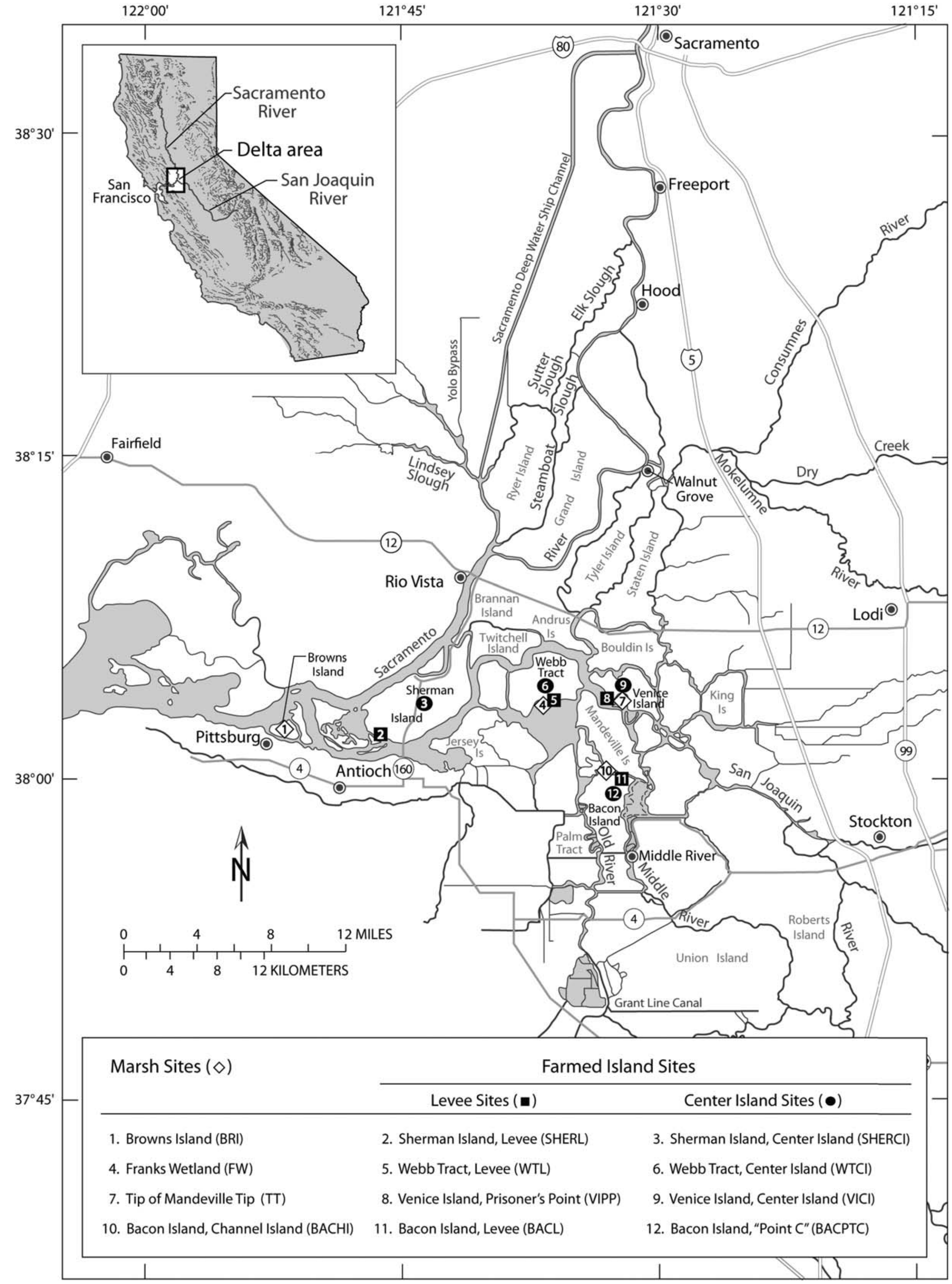

Figure 1. Map of the Sacramento-San Joaquin Delta showing all the marsh and farmed island coring sites and inset showing the location of the Delta in California, USA.

Table 1. Basic descriptions of coring sites in the Delta. Salinity data represent typical, non-drought conditions in adjacent sloughs and are based on Atwater (1980). Mixohaline (brackish) refers to a range of approximately 0–10 ppt, with higher salinities found during the dry season. Terminology follows Mitsch and Gosselink (2000), descriptions of hydrogeomorphic settings follow those described in Atwater (1980), and periods of drainage and levee building are from Thompson (1957). SR is Sacramento River, SJR is San Joaquin River, NA is not applicable.

Coring Site Name	Island size (ha)	Elevation (MSL in m)	Salinity Regime in Channel	Hydrogeomorphic Setting	Relative Energy Regime	Period of Drainage and Levee Building
Browns Island (BRI)	268	0.51	Mixohaline	Confluence of SR and SJR	High	NA
Sherman Island, Levee (SHERL)	4205	−4.44	Mixohaline	Confluence of SR and SJR	High	1870–1880
Sherman Island, Center Island (SHERCI)	4205	−4.52	Mixohaline	Confluence of SR and SJR	High	1870–1880
Franks Wetland (FW)	28	0.27	Fresh	Distributary of SJR, sheltered by natural marsh breakwaters, adjacent to permanently flooded farmed island	Very low	NA
Webb Tract, Levee (WTL)	2205	−5.18	Fresh	Main channel SJR and within historic floodplain of SR	Medium	1910–1920
Webb Tract, Center Island (WTCI)	2205	−7.25	Fresh	Main channel SJR within historic floodplain of SR	Medium to low	1910–1920
The Tip of Mandeville Tip (TT)	12	0.20	Fresh	Glacial outwash region in main channel of SJR	Medium	NA
Venice Island Prisoners' Point, Levee (VIPP)	1263	−4.52	Fresh	Glacial outwash region in main channel of SJR	Medium	1900–1910
Venice Island, Center Island (VICI)	1263	−6.95	Fresh	Glacial outwash region in main channel of SJR	Medium to low	1900–1910
Bacon Island, Channel Island (BACHI)	10	0.21	Fresh	Glacial outwash region along distributary of SJR	Low	NA
Bacon Island, Levee (BACL)	2257	−5.86	Fresh	Glacial outwash region along distributary of SJR	Low	1910–1920
Bacon Island, "Point C" (BACPTC)	2257	−6.28	Fresh	Glacial outwash region along distributary of SJR	Low	1910–1920

sites facilitated comparison of peat from both farmed and marsh islands. Study sites were chosen to incorporate the various environmental conditions in the Delta including salinity ranges, hydrogeomorphic settings, and energy regimes. Basic descriptions of each site are provided in Table 1.

The marsh islands are much smaller than the farmed islands. Because of their size, they were seen as undesirable for farming when most of the Delta was drained for agriculture, and, therefore, remain largely unaltered. Vegetation on these islands is dominated by emergent macrophytes and shrub-scrub wetland species. On Browns Island, the most brackish of the study sites, vegetation is dominated by *Schoenoplectus americanus* (American bulrush) and *Distichlis spicata* (salt grass). On Bacon Island Channel Island the overstory is dominated by *Salix lasiolepis* (arroyo willow) and the understory is dominated by *Cornus sericea* (red-osier dogwood) with smaller amounts of *Phragmites australis* (common reed) and *Rosa californica* (California wild rose). On Franks Wetland the vegetation is dominated by *C. sericea* and *S. lasiolepis*, with the coring site having a large population of *Athyrium filix-femina* (western lady fern). The Tip of Mandeville Tip is dominated by *C. sericea* and *S. lasiolepis*. Several species such as *Schoenoplectus acutus* (hardstem bulrush), *P. australis*, and *Typha* spp. are found at all sites. All nomenclature follows Hickman (1993).

On the farmed islands, farming practices have varied through the years. In the late 1880s, the most common crops throughout the Delta were potatoes, beans, and onions, which were staples of the region. In the early 1900s, barley covered the most extensive area, while potatoes, beans, and asparagus were the most valuable row crops. From the mid-1920s to 1950s, winter grain (mainly barley) and asparagus were the most common crops in terms of acreage, but field corn, alfalfa, milo, sugar beets, wheat, and rye were also important crops (Thompson 1957). Much of these farming practices have continued to recent times except that asparagus and sugar beet acreage has decreased substantially and field corn has become the major crop. On Sherman Island, Webb Tract, and Venice Island, the row crops over the past few decades include rotations of field corn, safflower, sunflower, winter wheat, milo, barley, and alfalfa (personal communications, David Forkel, The Delta Wetlands Project (Webb Tract and Bacon Island), Juan Mercado, CA Department of Water Resources (Sherman Island), and John Meek, Property Manager (Venice Island)). More recently, however, large areas of Sherman Island have been used for irrigated pasture, and Venice Island has been exclusively farmed for corn for the last five years. Differences in farming histories have little effect on subsidence rates according to Rojstaczer et al. (1991), who conducted transect surveys of three Delta islands (including Bacon Island) and found that only burning of the peat and not crop type had substantial effects on subsidence rates.

METHODS

Hydrologic Measurements

The artificial water table on farmed islands in the Delta is typically maintained between 0.6 to 2 m below the ground surface by a series of drainage ditches that run throughout the islands (Deverel et al. 2007, Deverel and Leighton 2008). For the four farmed islands in this study, the approximate depths to the water table from the land surface were estimated based on historical data (from Deverel and Leighton 2008), and/or conversations with farm managers. During the summer of 2006, Deverel and Leighton (2008) observed water levels in drainage ditches near the Sherman Island Levee site (site 2, Figure 1) at about 1.2 m below land surface. During visits to Webb Tract (sites 5 and 6) and Venice Island (sites 8 and 9) in early 2005, they also observed water levels in drainage ditches at about 1.0 m below land surface. Subsequent conversations with farm managers for these islands (Ralph Herringer, Webb Tract Farm Manager and John Meek, Venice Island Farm Manager, personal communications, 2008) indicated that water levels in drainage ditches on both Webb Tract and Venice Island are consistently maintained below 1.2 m. The coring site called BACPTC (site 12, Figure 1) was part of the surveying efforts described in Deverel and Leighton (2008) for estimating recent subsidence. They observed water levels in drainage ditches at 1.5 to 2 m below land surface on Bacon Island including the area near BACPTC.

Monitoring-well clusters for measuring groundwater levels were installed on Twitchell Island in the western Delta using a hollow stem auger. Wells were installed to depths of 0.3 to 10 m below land surface. In each borehole, 5.08-cm diameter, flush threaded, schedule 40, polyvinyl chloride pipe and stainless steel 0.0508-cm slotted well screens were installed. The annular space between the borehole wall and well casing was filled with clean #2–12 Lonestar sand to a depth of 30–60 cm above the well screen. The remaining annular space was filled with bentonite grout or cement. After well completion, wells were developed using surge block and bailer until water from the well was clear. Water levels were measured in wells approximately every four weeks. Additional information on water level measurements can be found in Deverel et al. (2007).

Peat Coring

On each of the farmed islands, peat coring was done both near the levee (far enough away to avoid any dredge materials) and near the center of the island because land-surface subsidence is known to be greater at the center of the islands (Ingebritsen and Ikehara 1999, Mount and Twiss 2005). Coring on the marsh islands was only done near the island centers. Peat cores were retrieved using a modified 5-cm-diameter Livingstone corer (Wright 1991). Cores were collected in multiple drives all the way to refusal in the underlying mineral sediment to ensure that the entire peat column was retrieved. Core drives were extruded, photographed, and visually described in the field. On the farmed islands, the uppermost oxidized and compacted soil layer was too dense for sampling with the Livingstone corer. Instead, samples were taken of the uppermost layer at 10–15 cm intervals using aluminum tins or polycarbonate tubing. In addition, occasionally a soil monolith was collected when the surface of the soil was too hard, too dense with roots, or too unconsolidated to collect with the Livingstone corer. Core drives were immediately wrapped in cellophane, placed in a cooler, transported to the laboratory, and stored in a refrigerator at approximately 3°C.

Surveying

In the fall of 2005, we conducted a real-time kinematic (RTK) geographic positioning system (GPS) survey using four base stations to obtain orthometric elevations and coordinates for each of the 12 coring sites. We used the best available benchmarks with published elevations for this initial survey. However, because the benchmarks available in the Sacramento-San Joaquin Delta are subject to land-surface subsidence, their stability and overall accuracy were uncertain. Therefore, to test the accuracy of the benchmarks, we conducted a static GPS survey at the same time the following year. Using overlapping control points and continuously operating reference stations (CORS), static survey heights of the four base stations were calculated (95% confidence interval = 0.008–0.031 m) to adjust the RTK base station heights. To correct for a systematic bias in the RTK measurements, a planar model was fit to the difference of the static and RTK ellipsoid heights of the benchmarks surrounding each of the base stations and then applied to the remaining RTK points for each survey. Ellipsoid heights were converted to orthometric elevations (NAVD88) using a GEOID03 model. Tidal benchmark LSS 13 (NOAA tidal station 9415064 situated near Antioch, CA) with a static surveyed ellipsoid height of −28.75 m was used to adjust the elevations of the coring sites to local mean sea level (MSL).

Laboratory Work

In the laboratory, cores were individually unwrapped, split lengthwise and immediately photographed. Core stratigraphy was documented, and one-half of each core was wrapped in cellophane and archived for future use. Bulk density was obtained for over 3100 samples by sectioning cores into 2-cm-thick blocks, measuring each dimension, obtaining wet weight of the sample, drying overnight at 105°C, and then weighing again to obtain dry weight (Chan 2002, Givelet et al. 2004). Samples from the oxidized and compacted soil from the farmed islands were processed similarly, except that sample blocks were generally larger in size, or remained in their original sample container during weighing and drying.

Initially, when length of the extruded core did not equal drive length, a linear factor was applied to account for compression. However, upon further investigation, we found that the majority of the uncorrected data better maintained its relationship between dimension dependent and non-dependent physical properties than the corrected data. In order to prevent contamination, we removed a small portion of sample from the top and bottom of some drives (generally < 4 cm) when it was visually apparent that the drives contained non-contiguous peat from elsewhere in the core. This was later confirmed in the lab by anomalous bulk density values for these portions of the drives. Therefore, removing the very top and bottom of some drives sufficiently accounted for any apparent compression and compaction in the coring process. The only correction made was for a soil monolith dug from the surface of Browns Island, which was corrected for expansion.

To determine percent organic matter (OM), standard loss on ignition (LOI) procedures were followed in which the dried bulk density samples were milled and heated to 550°C for 4 hours (Heiri et al. 2001). LOI analysis was done at 4-cm intervals both at the top meter of the core and at the bottom meter before contact with the epiclastic sediment underlying the peat. At all other places in the cores, LOI analysis was conducted at 10 cm intervals. On average, a duplicate LOI sample was run for every 9.5 samples. Average error for duplicates (error = |(duplicate A − duplicate B)/(larger of A or B)*100)|) was 0.74% (range = 0–4.8%). Nine-hundred samples were processed for LOI.

Total carbon was determined for 100 samples by the Department of Agriculture and Natural Resources (ANR) laboratory at the University of California, Davis (AOAC International 1997, Method 972.43). The samples were randomly selected from within each 1 m core segment of each core from every site. To avoid possible contamination, samples were not selected from the upper and lower 10 cm of each drive. For quality assurance, 13 blind samples were also submitted to complement the 14 duplicates run by the ANR lab as part of their quality control process. Duplicates averaged within 1.2% of each other. Several samples with the highest bulk density from each site were selected (for a total of 29 samples) and analyzed for carbonate following the method of the U.S. Salinity Laboratory Staff (1954). A mineral sediment sample within 22 cm of the contact with the overlying peat was included in this analysis for 11 of the sites to determine whether the mineral sediment could be a significant source of carbonate within the peat. The mineral sediment contained an average of less than 0.2% carbonate and the peat samples had an average of less than 0.4% carbonate, indicating that TC accurately approximates the organic carbon content of the peat.

Basal contacts of the peat columns with the underlying epiclastic sediment were generally sharp. At one site (BRI), however, the transition from peat to epiclastic sediment was gradual. Therefore, we also used the definition of an organic soil to differentiate peat from underlying mineral sediments. Saturated organic soils by definition must have an organic carbon content (by weight) of 1) $>$ 18% if the mineral fraction has 60% or more clay, 2) $>$ 12% if the mineral fraction contains no clay, or 3) $>$ 12% + (clay percentage multiplied by 0.1%) if the

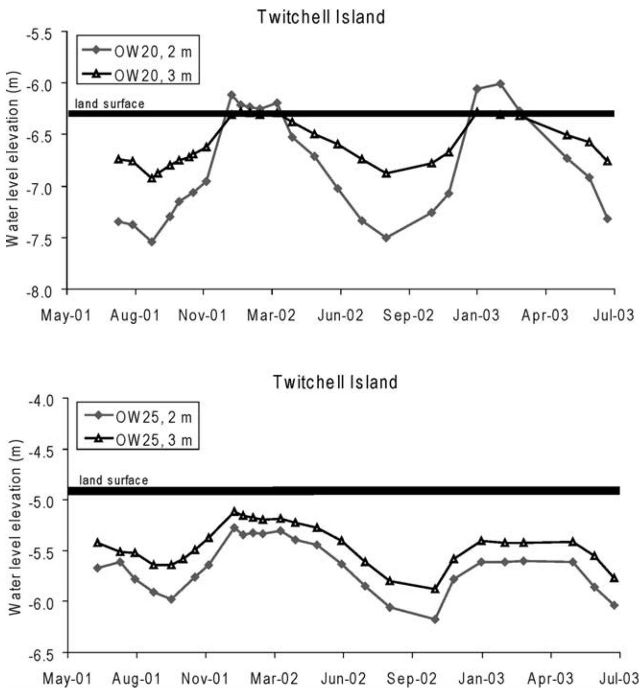

Figure 2. Ground water level elevation (m) relative to NGVD29 in A) observation well (OW) cluster 20 and B) OW 25 on Twitchell Island during May 2001 to July 2003.

mineral fraction contains less than 60% clay (USDA Soil Conservation Service 2006).

Organic fragments for radiocarbon analysis were sampled directly from the split core face where visible, or a 2- to 4-cm-thick sample of peat was sieved to concentrate achenes, charcoal, and other terrestrial macrofossils. Thirty-one radiocarbon samples were analyzed by Accelerator Mass Spectrometry (AMS) at the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory (LLNL) in Livermore, California. Ages were calibrated using CALIB (version 5.0.1 (Stuiver and Reimer 1993) with the INTCAL04 curve (Reimer et al. 2004).

Statistical Analysis

Analyses of variance (ANOVAs) were carried out for bulk density and % organic carbon to compare values between the three ''treatments'' (farmed center, farmed near the levee, and marsh) at the two levels of oxidation (oxidized or not oxidized). Of the six combinations of these effects, we had five of them in the study, because marsh cores did not contain an oxidized section. The error terms for the models were selected in order to account for the fact that some samples came from the same peat core (the paired oxidized and unoxidized samples), some came from different cores at the same site (near the levee and center samples), and some came from different sites (marsh versus center and near the levee). We assumed a variance component structure for the random effects corresponding to between-site, within-site and within-core variability. Each mixed model ANOVA was carried out using the Proc Mixed Procedure in SAS software (version 9.1, 2002–2003, SAS Institute, Inc., Cary, NC, USA). *Post hoc* comparisons (Tukey-Kramer) for the treatment*oxidized interaction terms were used to determine whether there were significant differences among the five combinations of the three treatment levels and the two levels of oxidation.

In order to compare bulk densities at particular values of % organic carbon, we first linearized both the bulk density and % organic carbon data with log transformations and then conducted an ANCOVA with % organic carbon as the covariate using the GLM procedure in SAS. Although the interaction term was less significant than the other factors, the fact that it still was significant precluded its removal from the analysis. We then used a least square means comparison of log(bulk density) to test the difference between site types for the relationship between bulk density and organic carbon content.

Lastly, a one-way ANOVA was used to determine whether there were differences in bulk density at different depths within the unoxidized peat from the farmed islands. *Post hoc* comparisons of the four depth intervals (0–50 cm, 50–100 cm, 100–150 cm, and 150–200 cm) were made using the Bonferroni adjustment.

RESULTS

Hydrologic Measurements

Ground-water data from observation well clusters on Twitchell Island, a typical farmed island in the western Delta, demonstrate seasonal fluctuations of ground-water levels (Figure 2). Beginning in fall, ground water levels start to rise due to the start of the wet season when 80% of the annual precipitation occurs (Thompson 1957). By late winter/early spring, ground-water levels typically reach their maximum values, sometimes even rising to the ground surface. During the spring season when precipitation tapers off, ground-water levels start to decline and continue to do so until the wet season returns by late fall to complete the cycle (Figure 2). Elevation Survey

The marsh land-surface elevations at the coring sites are 0.20–0.51 m above local MSL (Table 1, Figures 3 and 4). The Browns Island site is higher (0.51 m) than the other three marsh sites (0.20–0.27 m). On the farmed islands, the land-surface

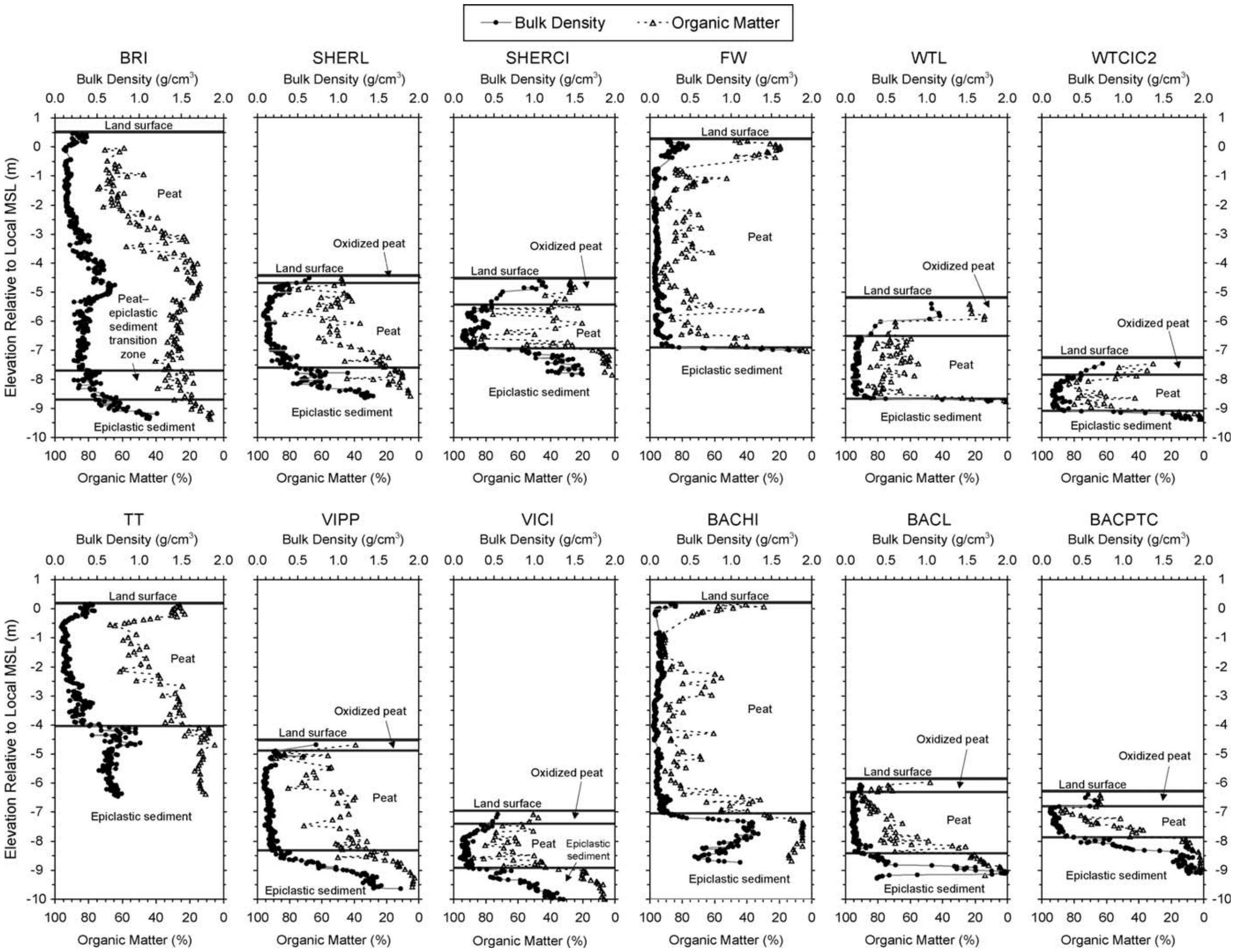

Figure 3. Elevation relative to local mean sea level versus bulk density and percent organic matter for the 12 cores. The land surface elevation, layer of oxidized peat, and elevation of the contact with epiclastic sediment are shown for each core.

elevations of the near levee (−5.86–−4.44 m) and center island (−7.25–−4.52 m) sites are well below local MSL (Table 1). Based on the height difference of 14 overlapping survey points from different base stations, the error of the core-site elevations is estimated to be ± 0.075 m.

Peat Coring

The thickness of peat in the marsh island cores ranges from 424 to 822 cm (Figures 3 and 4). Peat in the marsh cores largely contains roots, rhizomes, stems and other plant fragments of bulrushes (*Schoenoplectus* spp.), cattails (*Typha* spp.) and reeds (*P. australis*) in variable states of decomposition. The peat typically has a homogeneous appearance, without layering. The top ~1 m of peat below the marsh surface generally contains a thick root mat of live vegetation. Silt and clay are the primary inorganic components of the peat. Concentrations of silt and clay are usually insufficient to form obvious stratigraphy except for a visible zone of gray clay and silt-rich sediment that is within the upper 50 cm at all marsh sites.

The top 0.25–1.34 m of soil on the farmed islands consists of highly compacted, oxidized, and decomposed peat with no apparent stratigraphy (Figures 3 and 4). Below this surface layer lies an unoxidized peat layer. The top of the unoxidized peat has a 10 cm or less layer of dense but otherwise intact peat containing layered plant fragments. The bulk density of the unoxidized peat below this dense layer generally decreases with depth, and often has a very uncohesive soil structure. At further depth, the peat has a similar appearance to the peat found at the marsh sites. At all sites, the peat column is

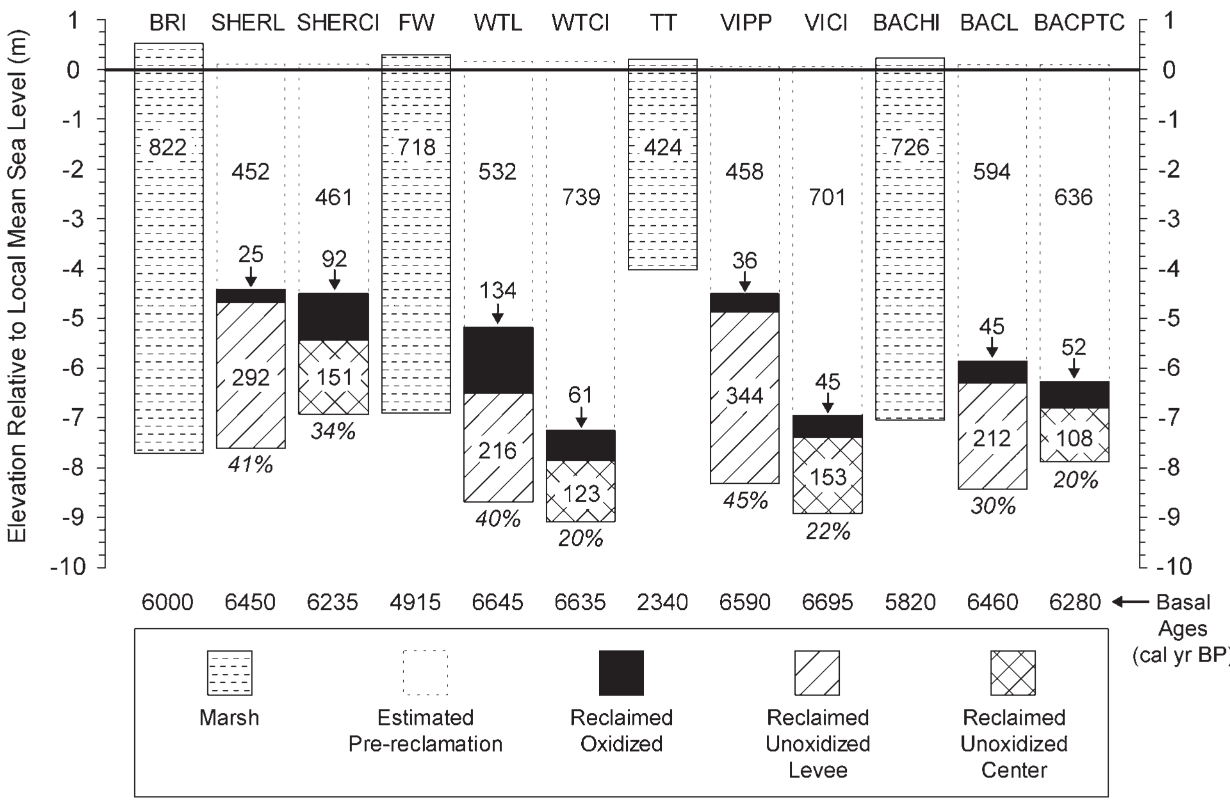

Figure 4. Elevation relative to mean sea level and peat thicknesses for the 12 cores. Numbers shown in each columns are the peat thicknesses in centimeters. The values in italics are the estimated percentage of the original peat column that remains. Basal ages are the median probability of the oldest age obtained from achene samples. (To estimate the original, pre-drainage peat thickness and percentage of peat that remains, we assumed that the initial land surface elevations of farmed islands were similar to the present day elevations of nearby marsh islands.) Initial land-surface elevations were corrected for eustatic sea-level rise, and regional neotectonics was assumed to be negligible since drainage.

underlain by a relatively sharp stratigraphic contact with epiclastic sediment that consists of clay and silt with occasional sand.

The percent total carbon (TC) was used to approximate percent organic carbon (OC) because analyses showed that carbonate was $<<$ 1%. LOI values were converted to OC values using a regression in which OC = 0.55(OM) – 2.69 (r^2 = 0.98, p = 0.0003, OM = organic matter,). There are no significant differences between the OC values for any of the treatments at the two levels of oxidation (treat.*oxid. comparisons, Table 2c), although for the paired sites, farmed center and farmed near the levee, the mean OC is just barely out of significance range for oxidized vs. unoxidized samples (Table 2a).

Mean bulk density ranges from approximately 0.16 to 0.65 g cm^{-3} in the peat from the different treatment groups (Table 3b). The bulk density of the oxidized peat from the farmed islands (both center island and near levee sites) is significantly higher than the marsh island peat (treat.*oxid. comparisons, Table 3c). The oxidized peat from center island cores does not have significantly higher bulk density than the oxidized peat near the levees (Table 3c). Marshes have elevated bulk density typically only in the upper 50 cm (0.31 $\pm$ 0.05 g cm^{-3}, mean $\pm$ standard deviation) due to a higher proportion of epiclastic sediment in this part of the core (Figure 3).

Bulk density (BD) values for peat from most of the farmed sites (near levee and center island sites) are greater than those for the marsh sites at a given organic carbon content (Figure 5a). The regression curve for the marsh sites is shown for reference to illustrate the bulk density and organic carbon content of relatively undisturbed peat (OC = $5.33(BD)^{-0.82}$, r^2 = 0.88). For the farmed center island sites, this pattern of greater bulk density at a given organic carbon content is even stronger (Figure 5b). This is not surprising, as the peat from these sites has undergone the greatest subsidence and thus, the greatest compaction. The relationship between BD and OC was further substantiated by an ANCOVA with bulk density as the dependent variable and % organic carbon as the covariate. The resulting least squares means comparison

Table 2. Results from ANOVA of % organic carbon in peat: (a) tests of fixed effects, (b) least squares means (effect = treatment × oxidized), and (c) differences of least squares means using the Tukey-Kramer adjustment.

(a)

Effect	Num. degrees of freedom	F value	P
treatment	2	0.16	0.8519
oxidized	1	6.18	0.0511
treat.*oxid.	1	0.26	0.6310

(b)

Treatment	Oxidized	Estimate	SE	t value	P
Farmed center	No	31.9377	4.2041	7.60	<0.0001
Farmed center	Yes	22.8622	4.4461	5.14	0.0001
Farmed near levee	No	31.1638	4.1047	7.59	<0.0001
Farmed near levee	Yes	25.1694	4.6569	5.40	<0.0001
Marsh	No	28.7907	4.0445	7.12	<0.0001

(c)

Treatment	Oxidized	Treatment	Oxidized	Estimate	SE	t Value	P	Adj. P
Farmed center	No	Farmed center	Yes	9.0755	4.2203	2.15	0.0803	0.3178
Farmed center	No	Farmed near levee	No	0.7738	5.8757	0.13	0.8975	0.9999
Farmed center	No	Farmed near levee	Yes	6.7682	6.2739	1.08	0.2984	0.8113
Farmed center	No	Marsh	No	3.1470	5.8338	0.54	0.6003	0.9791
Farmed center	Yes	Farmed near levee	No	−8.3016	6.0512	−1.37	0.1937	0.6654
Farmed center	Yes	Farmed near levee	Yes	−2.3072	6.4386	−0.36	0.7248	0.9954
Farmed center	Yes	Marsh	No	−5.9285	6.0105	−0.99	0.3428	0.8522
Farmed near levee	No	Farmed near Levee	Yes	5.9944	4.3522	1.38	0.2208	0.6626
Farmed near levee	No	Marsh	No	2.3732	5.7626	0.41	0.6887	0.9922
Farmed near levee	Yes	Marsh	No	−3.6212	6.1681	−0.59	0.5668	0.9718

between log(BD) on the farmed vs. marsh islands was highly significant ($F_{3,330} = 298.97$, $p < 0.0001$).

On the farmed islands, increased bulk density, which is an indication of compaction, decreases with depth within the unoxidized peat zone (Figure 5c). The upper 50 cm of the unoxidized peat column has significantly higher bulk density than the 50–100 cm depth interval ($F_{3,587} = 37.763$, $p < 0.0001$, Bonferroni *post hoc* comparison, $p < 0.0001$). In addition, bulk density at the 50–100 cm depth is greater than at 100–150 cm depth ($p < 0.001$). Between 100–150 cm and 150–200 cm depth, however, there is no significant difference in bulk density ($p > 0.05$) indicating that compaction ceases to be measurable beyond 100–150 cm.

The peat that remains on the farmed islands represents an estimated 20–45% of the original peat resource prior to drainage for agriculture. The center island sites have lost more peat than each of their associated levee sites (Figure 4). The estimated loss of peat thickness is between 450–740 cm, depending on the island (Figure 4). In order to estimate the carbon loss at each of the center island sites (where most of the farming occurs), we simply subtracted an estimate of the total remaining carbon pool on each island (calculated using all the BD and % OC data for both unoxidized and oxidized portions of each core and peat thicknesses from Figure 4) from the estimated total pre-drainage carbon pool on each of the islands (calculated using mean BD and mean % OC content of undisturbed peat for each island and the estimated pre-drainage peat thicknesses from Figure 4). These calculations indicate that there has been an estimated loss of between 2900–5700 metric tons organic C/ha at the center island sites. Of all the sites, the center island site at Webb Tract is estimated to have lost the most peat since drainage for agriculture. Both Webb Tract and Bacon Island Point C have lost all but about 20% of their original peat layer.

Since drainage for agriculture, the average rate of total subsidence from both primary and secondary factors on the farmed islands ranges from approximately 3.5–8.2 cm yr^{-1}. These estimates of the pre-drainage peat thickness, the percentage of peat that remains, and rates of subsidence assume that the initial land-surface elevations of farmed islands were similar to the

Table 3. Results from ANOVA of bulk density of peat: (a) tests of fixed effects, (b) least squares means (effect = treatment × oxidized), and (c) differences of least squares means using the Tukey-Kramer adjustment.

(a)

Effect	Num. degrees of freedom	F value	P
treatment	2	0.41	0.6749
oxidized	1	36.79	0.0003
treat.*oxid.	1	0.05	0.8288

(b)

Treatment	Oxidized	Estimate	SE	t value	P
Farmed center	No	0.2147	0.07294	2.94	0.0113
Farmed center	Yes	0.6528	0.07586	8.61	<0.0001
Farmed near levee	No	0.1580	0.07280	2.17	0.0491
Farmed near levee	Yes	0.5649	0.07826	7.22	<0.0001
Marsh	No	0.1854	0.07273	2.55	0.0243

(c)

Treatment	Oxidized	Treatment	Oxidized	Estimate	SE	t Value	P	Adj. P
Farmed center	No	Farmed center	Yes	−0.4381	0.09761	−4.49	0.0024	0.0137
Farmed center	No	Farmed near levee	No	0.05678	0.1031	0.55	0.5909	0.9786
Farmed center	No	Farmed near levee	Yes	−0.3501	0.1070	−3.27	0.0051	0.0661
Farmed center	No	Marsh	No	0.02938	0.1030	0.29	0.7800	0.9982
Farmed center	Yes	Farmed near levee	No	0.4948	0.1051	4.71	0.0003	0.0104
Farmed center	Yes	Farmed near levee	Yes	0.08793	0.1090	0.81	0.4315	0.9212
Farmed center	Yes	Marsh	No	0.4674	0.1051	4.45	0.0005	0.0143
Farmed near levee	No	Farmed near levee	Yes	−0.4069	0.09938	−4.09	0.0035	0.0224
Farmed near levee	No	Marsh	No	−0.02740	0.1029	−0.27	0.7942	0.9986
Farmed near levee	Yes	Marsh	No	0.3795	0.1068	3.55	0.0029	0.0455

present day elevations of nearby marsh islands. The estimates were corrected for the total eustatic sea level rise since drainage for agriculture by subtracting 19.5 cm (which is the estimated global mean sea-level rise for the period between 1870–2004; Church and White 2006) from the total land-surface subsidence at each site. It is assumed that regional subsidence from ground water and gas withdrawal has been negligible (Rojstaczer et al. 1991). Because there are no available data, the

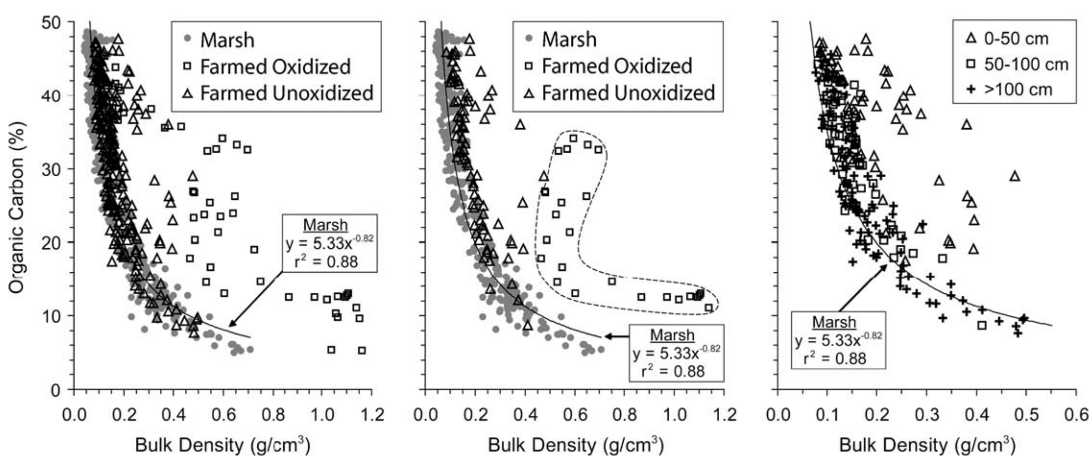

Figure 5. Percent organic carbon versus bulk density of peat for A) all marsh and farmed island sites, B) marsh sites and farmed center island sites, and C) unoxidized peat on the farmed islands by depth. The regression curve for marsh island sites shows the properties of relatively undisturbed peat.

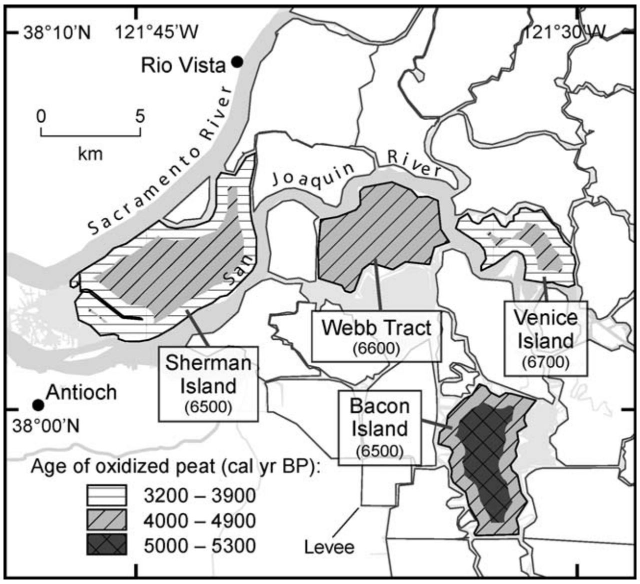

Figure 6. Estimated age of the surface of the intact, unoxidized peat that underlies the oxidized peat layer currently being farmed in the Delta. Two sets of estimated ages are shown for each island: a younger zone around the island perimeter, and an older zone encompassing the central part of the island (widths of the zones are not to scale). On Webb Tract, the coring location is near the island drain, resulting in an older age than would normally be expected for unoxidized peat near a levee. Numbers in parentheses are the median probability of the age (cal yr BP) of the basal peat determined from achenes found within the peat on each island.

degree of uplift or subsidence from natural factors such as neotectonic activity during this period could not be included in the analysis.

The most consistent and dependable peat ages were found using achenes for radiocarbon analysis. Wells (1995) also found this to be the case. Charcoal samples were used when no achenes were available from a particular depth range. The basal ages of peat at all the coring sites range from 2160 to 6790 calibrated years before present (cal yr BP). The oldest median basal dates are from the center island site on Venice Island (median age: 6695; 2-sigma range: 6570–6785 cal yr BP) and the levee site on Webb Tract (median age: 6720; 2-sigma range: 6665–6790 cal yr BP). On the farmed islands, the age of the relatively undisturbed peat that is directly below the currently farmed soil layer ranges from 3200 to 5300 cal yr BP (Figure 6).

DISCUSSION

The Sacramento-San Joaquin Delta is a prime example of the environmental impacts that can result from draining peatlands for agriculture. Such activities spur a complex chain of land-surface subsidence processes that begin with a brief period of primary subsidence and continue with long-standing secondary subsidence. The legacy of wetland drainage for agriculture can best be illustrated by a conceptual model (Figure 7). Although this model was created for the Delta *per se*, the basic processes of land-surface subsidence can be applied to many other drained wetlands containing peat soils. In the following discussion, we use this conceptual model to explain the complex processes that transformed a 1400 km^2 tidal marsh region into the Delta of today.

Before drainage for agriculture, the farmed islands had surface elevations that were slightly above local mean sea level. The elevation of the

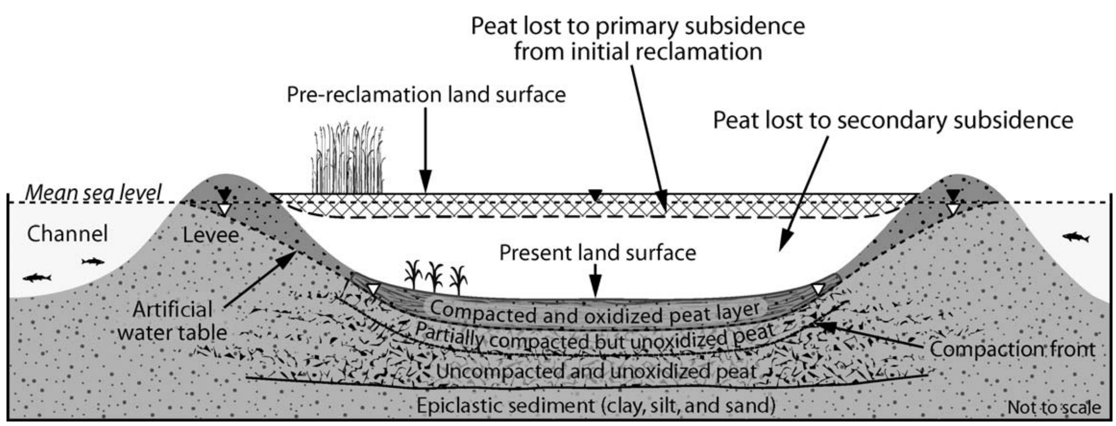

Figure 7. Conceptual diagram of the peat column and underlying sediment on farmed islands with constructed levees. Dotted lines represent the water table. Solid triangles indicate the elevation of the water table prior to drainage. Open triangles indicate the elevation of the artificial water table currently used to maintain an aerobic rooting zone. The artificial water table is shown here at its lowest typical elevation. Although mean sea level has changed slightly since the time of wetland drainage, here it is shown to be constant relative to the much greater land-surface subsidence processes. On some islands or parts of islands, uncompacted and unoxidized peat layers no longer exist.

water table on the islands would have been the same as the elevation of the water in the adjoining channels (Figure 7). These conditions had prevailed in the Delta since peat began forming about 6700 years ago (Figure 4), which is consistent with the stabilization of sea-level rise at about 7000 years ago (Day et al. 2007). Before that time, from the last glacial maximum about 18,000 years ago until stabilization, sea-level rise was about 1–2 m per century, which was too rapid for marsh formation to keep pace with sea-level rise (Atwater et al. 1979).

Beginning in the mid-1800s, the first step in converting wetlands to farm fields was the construction of artificial levees to exclude floods and tidal overflow. Such construction drained the soil, creating the aerobic rooting zone required for agriculture (Figure 7). Levee-building was needed because most of the islands in the south-central Delta did not have natural levees (Atwater et al. 1979, Atwater and Belknap 1980). However, even where channels were flanked by natural levees, man-made levees were built in order to straighten irregular sinusoidal shorelines. Levees were routinely placed on poor foundations of peat and highly organic sediments (Prokopovich 1985). Subsequent to levee construction, the main drainage ditches were installed on the islands. Thus began the drainage of the islands, which resulted in primary subsidence through settling and compaction of the peat (hatched zone, Figure 7). Historical accounts state that primary subsidence was on the order of 0.6 m (Weir 1950). In the 1920s, it was believed that land-surface subsidence was caused by compaction of the peat from heavy agricultural equipment, and that subsidence would be self-limiting with the completion of near-surface compaction (Weir 1950, Prokopovich 1985). However, initial primary subsidence was then followed by decades of secondary subsidence (Weir 1950, Thompson 1957, Rojstaczer and Deverel 1995, Deverel et al. 1998).

Secondary subsidence, or long-term subsidence, has occurred mainly as a result of microbial oxidation of the highly organic, peat soils in the Delta (Deverel and Rojstaczer 1996). From the mid-1880s until today, the elevation of the artificial water table has determined the thickness of the aerobic rooting zone, and, in so doing, created an active zone of secondary subsidence. The thickness of this active zone (i.e., depth to the artificial water table) typically ranges from 0.6–2 m throughout the Delta (Deverel et al. 2007, Deverel and Leighton 2008). During the wet season, the thickness of this zone of secondary subsidence usually decreases due to seasonal fluctuations in ground water level (Figure 2). On farmed islands, the elevation of the water table has typically been higher near the levees than near the center of the islands. This has resulted in a thinner oxidized peat layer near the levees than at the island centers (Figure 7). The Webb Tract levee site is an exception to this pattern due to its location near the main island drain where the water table is lower than typically found near a levee. This is consistent with studies outside the Delta that have found that subsidence tends to increase with proximity to drainage channels (Burke 1963, Brandof 1992).

Through time, the lower water table elevation at the island centers has resulted in the typical ''saucer-'' or ''bowl-shape'' of the farmed islands in the Delta. Earlier studies (e.g., Weir 1950, Prokopovich 1985, Ingebritsen and Ikehara 1999, Ingebritsen et al. 2000) in the Delta have attributed this to higher carbon content (and thus more material available for oxidation) and thicker deposits of peat near the center of the islands. However, the organic carbon content of unoxidized peat at the center and near levee sites was found not to differ statistically (Table 2). Furthermore, some of the levee sites appear to have had greater initial peat thickness than their center island sites (Figure 4). Therefore, although peat carbon content and initial peat thickness are certainly important factors with respect to subsidence, the elevation of the artificial water table is clearly more important. The continuous lowering of the artificial water table to keep pace with land-surface subsidence initiates *de facto* primary subsidence (settling and compaction) in addition to secondary subsidence (primarily microbial oxidation), the sum of which is the total subsidence occurring on the islands. In a study of North Carolina wetlands by Ewing and Vepraskas (2006), primary subsidence was estimated to comprise two-thirds of the total subsidence during the first 30 years of drainage. In contrast, in the Delta, where subsidence has occurred over a much longer period, secondary subsidence plays a more prominent role in total subsidence.

Due to both primary and secondary subsidence, 20–45% of the estimated original peat layer remains at the center of the islands studied (Figure 4). This translates into an estimated loss of approximately 2900–5700 metric tons organic C/ha for the center island sites. The youngest remaining unoxidized peat on the farmed islands formed more than 4000 years ago (Figure 6). As expected, the thickness of the remaining peat increases and age of the remaining peat decreases with proximity to the levees. The centers of Bacon Island, Webb Tract, and Venice Island have only about 20% of the estimated initial peat column remaining (Figure 4). Since drainage of the islands, the average rate of total subsidence from both primary and secondary factors ranges from 3.5–8.2 cm yr^{-1}. This rate is consistent with rates of subsidence previously estimated for the Delta (Rojstaczer and Deverel 1995, Deverel et al. 1998) and for drained wetlands elsewhere in the world (Stephens et al. 1984, Prokopovich 1985, Ewing and Vepraskas 2006).

The impact of land-surface subsidence can even be seen in the unoxidized peat on the farmed islands. Overall, at a given carbon content, the bulk density of peat on the farmed islands is greater than on the marsh islands. On the farmed islands, compaction extends approximately 1 m down into the unoxidized peat layer. This 1-m zone comprises the majority of the remaining peat column at the center island sites. This clearly demonstrates that subsidence is not strictly a surficial process, but affects the unoxidized peat that is well below the artificial water table. The compressive effects of subsidence below the water table have also been recognized in a study of drained wetlands in North Carolina (Ewing and Vepraskas 2006), a drained peatland in Canada (Price and Schlotzhauer 1999), and drained peat domes in Malaysia (Kool et al. 2006).

In the Delta as well as other marsh regions drained for agriculture, loss of peat largely through microbial oxidation will continue as long as the artificial water table is maintained well below the soil surface. Switching to crops that require a shallower aerobic rooting zone and hence an artificial water table closer to the surface will reduce land-surface subsidence, but will not halt the process. For example, Gambolati et al. (2005) calculated that in drained marshes in the Venice Lagoon watershed, which are also undergoing land-surface subsidence due to microbial oxidation, peat would disappear in 65 years if the water table were 60 cm from the surface, but would last 200 years if the water table were 20 cm from the land surface. With changes in water management practices, similar conservation of the remaining peat may be possible in the Delta and elsewhere. However, the complete cessation of land-surface subsidence is only possible through total and permanent saturation of the remaining peat.

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